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Reflection echelon and echelette gratings as antennas in quasi-optical millimeter wave bands

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Abstract : We have examined the possibilities of diffraction gratings like reflection echelons and echelettes to be used as antennas in the quasi-optical millimeter wave bands which are characterised with wellknown advantages of having broad band-width, narrow beam-width, small size, light weight and high antenna gains. We also discuss the method of construction of such grating antennas with minimum construction cost but having maximum diffraction intensity.

Keywords : Millimeter wave, diffraction grating, antenna, echelon, echelette

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1. Introduction

The millimeter wave region of the electromagnetic spectrum lies between the far infrared and microwave region. Frequencies generally attributed to this portion are in the range 30–300 GHz or 1 cm to 1 mm wavelength band. These waves possess a number of important advantages for such applications as communication, guidance and sensing. These advantages include a large effective rf bandwidth, which solves the spectrum crowding problem; a narrow effective beamwidth, which yields greater resolution; receivers and antennas of small size and usefulness for integrated designs, with inherent characteristics of ruggedness, reproducibility and reliability.

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In the last few decades many optical principles have been utilised in the construction of microwave zone plate antennas [1–3], microwave lens antennas [4–6] and mm wave lens antennas obtained by lens shaping techniques [7]. Different kinds of diffraction gratings are being used in wave guide devices [8,9], infrared and mm wave astronomy [10–13]. It is to be noted that there exists at present, resonant planer antennas like microstrip patch, half-wave dipole array, half-wave slot, tapered slot *etc*. in quasi-optical regions [14].

Reflection echelons and echelettes are wellknown for their high resolving power and diffraction efficiency and we anticipate that such gratings will be more advantageous as quasi-optical antennas with respect to the existing conventional antennas. In this paper therefore, we attempt to investigate the use of such gratings in the mm and sub-mm wave bands which have aroused much interest and enthusiasm in the field of astrophysics and space science research.

2. Theoretical analysis

The intensity (J) of the diffracted waves from a reflection echelon [15] is given by,

$$J = \left\{\frac{b \sin\left(\frac{b\gamma}{2}\right)}{\frac{b\gamma}{2}}\right\}^2 \left\{\frac{\sin\left[\frac{N(\beta - b\gamma)}{2}\right]}{\sin\left(\frac{\beta - b\gamma}{2}\right)}\right\}^2, \tag{1}$$

where $\beta = \frac{2\pi d}{\lambda}(1 + \cos\theta)$,

$\gamma = \frac{2\pi}{\lambda}\sin\theta$,

b = breadth of each step,

d = depth of each step,

θ = diffraction angle,

and λ = operating wavelength.

The diffracted intensity from a reflection echelette [16] is given by,

$$J = \frac{4\sin^2\frac{1}{2}Nk\Psi}{k^2\sin^2\frac{1}{2}k\Psi}\left[\left(\frac{1}{v}\sin\frac{kva}{2} - \frac{1}{\gamma}\sin\frac{k\gamma b}{2}\right)^2 + \left(\frac{4}{\gamma v}\sin\frac{kva}{2}\sin\frac{k\gamma b}{2}\cos^2 k\Psi\right)\right] \tag{2}$$

where N = total number of facets of the echelette,

$k = \frac{2\pi}{\lambda}$, λ being the operating wavelength and a, b, v, γ and Ψ are constants determined by the geometrical parameters of the grating.

We shall now discuss the results obtained from eqs. (1) and (2). Observations reveal that the diffraction-limited systems are constrained in their angular resolution by the wave nature of light. Rigorous theory has been proposed to treat the diffraction of beams of radiation. Further simplification is induced by assuming that the beam of radiation has a Gaussion amplitude distribution. Such type of beam propagation is of great practical utility since most high performance feed horns have radiation patterns that are very nearly Gaussian.

It will not perhaps be out of place if we discuss therefore, the basic characteristics of such beam propagation. Let us assume that the radiation is nearly a plane wave as is really the case for the diffracted waves from echelons and echelettes. Let the wave be propagated along the Z-axis so that the Z-dependence is of the form $\exp(-ikZ)$. For the fundamental Gaussian mode, the electric field distribution [14] is given by

$$\Psi(Z) = A \frac{W_0}{W(Z)} \exp\left[\frac{-r^2}{W^2(Z)}\right] \exp(-ikZ) \exp\left[\frac{i\pi r^2}{\lambda R(Z)}\right] \times \exp\left[i \tan^{-1} \frac{\lambda Z}{\pi W_0^2}\right], \tag{3}$$

where $\quad r = \left(x^2 + y^2\right)^{1/2}$.

The first exponential term contains the Gaussian amplitude variation perpendicular to the axis of propagation. For higher order modes, the expression should be multiplied by Laguerre polynomial. The quantity W is the beam radius and is a function of Z, the minimum value of which is W_0. The second exponential term represents the plane-wave phase shift. The third term gives the phase produced by a spherical wave-front having radius of curvature R, which is also a function of Z. The final term gives the phase difference between the plane wave and the Gaussian beam. The term $|\Psi(Z)|^2$ evidently represents the power density.

All Gaussian modes possess the same dependence of W and R on Z as shown below

$$W(Z) = W_0\left[1 + \left(\frac{\lambda Z}{\pi W_0^2}\right)^2\right]^{1/2} \tag{4}$$

and

$$R(Z) = Z\left[1 + \left(\frac{\pi W_0^2}{\lambda Z}\right)^2\right]. \tag{5}$$

The Gaussian beam-growth away from the beam-waist is shown in Figure 1. Such a beam with negligible truncation preserves its form during its propagation. For most system application, it is however necessary to focus the beam. Focussing elements for such beams may be refractive, using low-loss dielectric materials, or reflective, employing off-axis conic sections. A typical transformation of a Gaussian beam by a thin lens of focal length

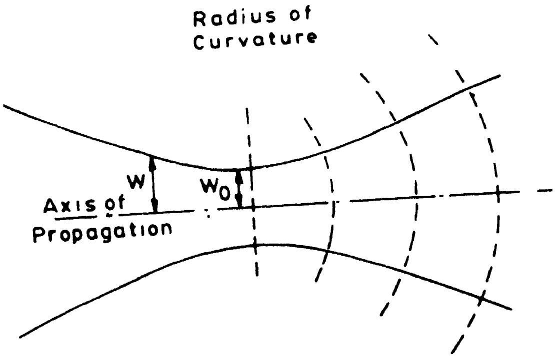


Figure 1. Gaussian beam propagation.

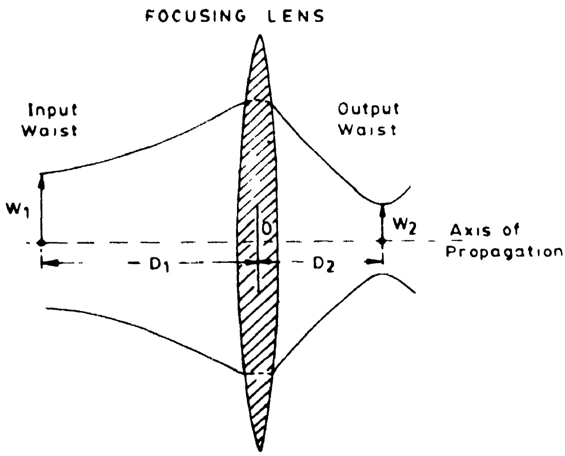


Figure 2. Gaussian beam transformation by a thin lens of focal length f.

f is depicted in Figure 2. The distances of the input (W_1) and the output waist (W_2) [14] is given by

$$D_2 = f\left[1 + \frac{\dfrac{D_1}{f-1}}{\left(D_1/f-1\right)^2 + \left(\pi W_1^2/\lambda f\right)^2}\right]. \tag{6}$$

The system magnification M, has been found to be

$$M = \frac{W_2}{W_1} = \left[\left(\frac{D_1}{f} - 1\right)^2 + \left(\frac{\pi W_1^2}{\lambda f^2}\right)^2\right]^{-2}. \tag{7}$$

The eq. (7) is graphically represented in Figure 3. With the help of eqs. (6) and (7), it is possible to design a Gaussian beam optical system to transform a given waist to another waist at a specific distance away.

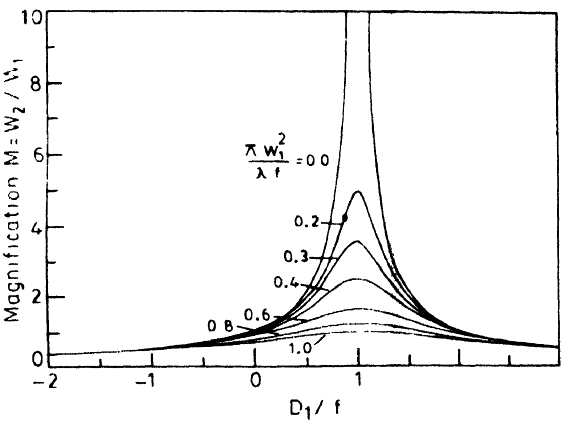
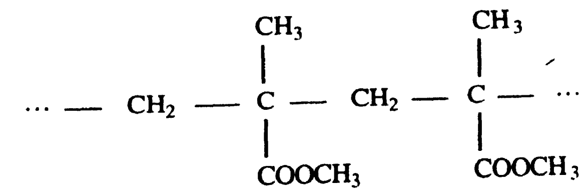


Figure 3. Magnification M as a function of distance to input waist d_1/f for various values of $\frac{\pi W_1^2}{\lambda f}$

3. Construction of mm wave diffraction grating antennas

Quasi-optical mm wave diffraction gratings may be divided into two classes *viz*, transmission type and reflection type. For the construction of transmission type diffraction gratings in the mm wave region, we require suitable dielectrics with low tangent loss. To meet this requirement, we usually prefer two dielectric materials called Polymethyl Methacrylate *i.e.*, Mylar and High Density Polyethylene (HDP). The refractive indices of these materials are around 2.1 and 2.3 respectively. Both the materials possess very low tangent loss of the order of 10^{-4} near the frequency range 90–300 GHz.

Mylar is a transparent polymer called Polymethyl Methacrylate, whose structural formula is given by,



It readily dissolves in acetone, chloroform and ethyl acetate. Basically Polymethyl Methacrylate may be looked upon as a polyethelene chain in which one hydrogen at each second carbon is replaced by an ester group – $COOCH_3$. The constructions of mm wave transmission echelons and echelettes have been discussed elsewhere [17].

It is to be noted in this context that the absorption is a significant limitation for refractive optics. The main advantage of reflective optics, in this respect, is the absence of dielectric mismatch and absorption. It may be mentioned in this connection that the fractional power loss is approximately 10^{-3} at 300 GHz [14] for each reflection from a metal surface. Let us therefore, confine our discussion to the reflection echelon and echelette to be used as mm wave antennas. An echelon grating can be constructed out of a highly polished metal like silver, aluminium or copper and the steps should be of the order of cms. It is to be fabricated over a quartz base substrate as shown in Figure 4a. Quartz is an excellent absorber of mm waves and therefore will prevent the transmission of leaky waves, if any, through the metal surface. Echelette reflecting grating is also similarly constructed after properly blazing the highly polished metal surface and finally fabricating it over a quartz substrate as shown in Figure 4b. The size of each facet should be of the order of cms.

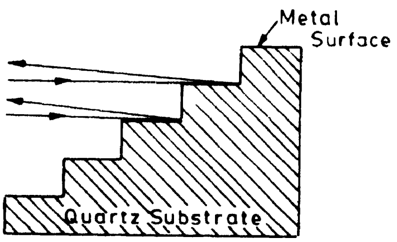


Figure 4a. mm wave reflection echelon

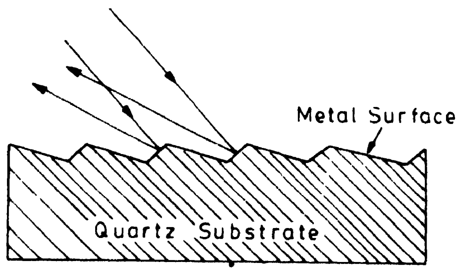


Figure 4b. mm wave reflection echelette.

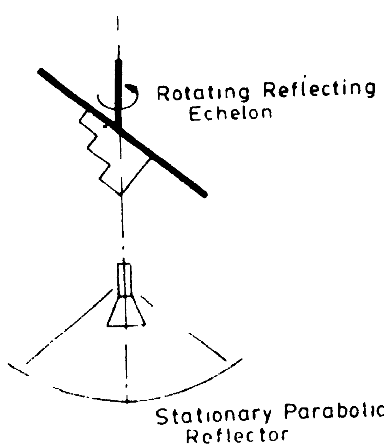


Figure 5a. Mechanically scanned reflector antenna with rotating reflecting echelon.

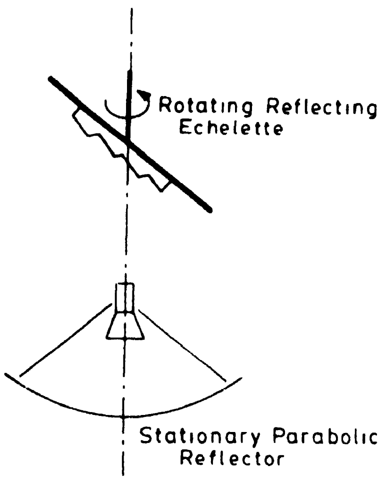


Figure 5b. Mechanically scanned reflector antenna with rotating reflecting echelette.

As mentioned earlier, a variety of antennas has been designed for the mm wave band such as reflector, lens feed horn antennas along with microstrip mm wave antennas, antennas derived from open mm wave-guides and integrated antennas [18,19]. Let us consider a typical case which involves mechanically scanned reflector antennas, which have small size and weight and are very suitable for rapid beam scanning. A simple antenna of such kind operates with two reflectors, a feed-horn parabolic reflector which remains stationary and a planar reflector which rotates about the antenna axis [20]. The directivity gain is determined by the parabolic reflector and the direction of radiation by a planar reflector. Such antennas are useful for surveillance and tracking. If a design is used where the inclination angle of the rotating mirror can be varied during scans, a two-dimensional scan pattern can be obtained. A rotating echelon or an echelette can be used in place of rotating planar reflector as sketched in Figures 5a and 5b where we can expect an extra advantage of higher resolution. If the stationary mirror uses a cassegrainian feed instead of horn feed, it will increase the efficiency and reduce pattern distortions. It may be mentioned that this arrangement also cannot completely avoid distortions. An off-set feed horn perhaps is the ideal answer in such cases.

4. Results and discussion

Let us now consider the intensity pattern obtained from a reflection echelon grating from eq. (1). We consider a three dimensional plot for intensity distribution as a function of relative sizes of the steps *i.e.*, b and d. The graphs represents an important orderlines. The peaks are found to be arranged systematically in different straight lines which are more or less parallel to each other. The situation is represented in Figure 6(a). The parameters are $N = 30$, $b = d =$ 1 cm to 10 cm. $\lambda = 0.5$ and $\theta = 5°$. The Figure 6(b) represents the state of affairs when we

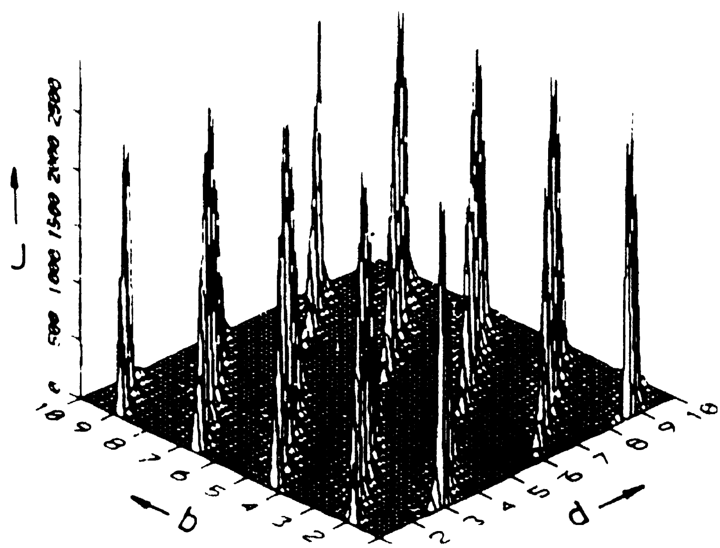


Figure 6a. 3D plot for intensity distribution as a function of step parameters b and d. Here $N = 30$, $\lambda = 0.5$ cm, b and d is varied from 1 cm to 10 cm.

reduce the number of steps N to 10 keeping the other parameters unchanged. From the 3D intensity plots and its contour diagrams [21], the minimum geometric parameters b and d corresponding to maximum intensity are chosen. This will reduce the construction cost also.

The method has been discussed in detail in our previous work [21]. A graph between intensity (J) *vs* angle of diffraction (θ), derived from eq. (2) for an echelette reflection

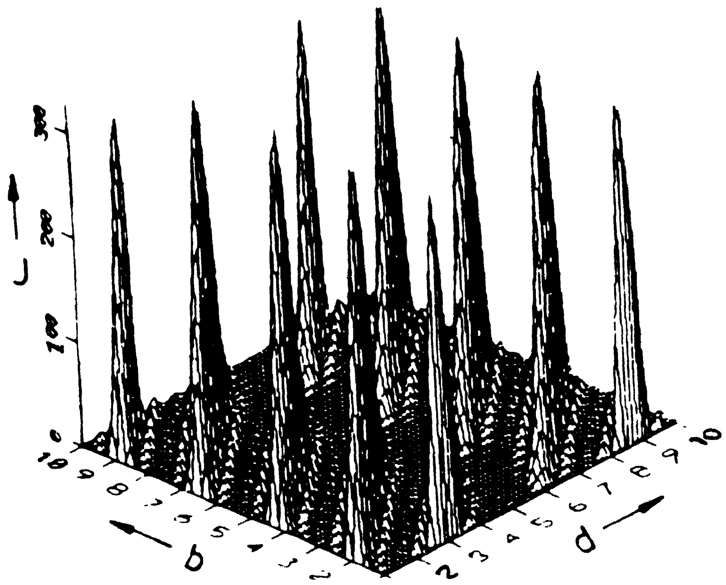


Figure 6b. 3D plot for intensity distribution as a function of step parameters b and d. Here $N = 10$, $\lambda = 0.5$ cm, b and d is varied from 1 cm to 10 cm.

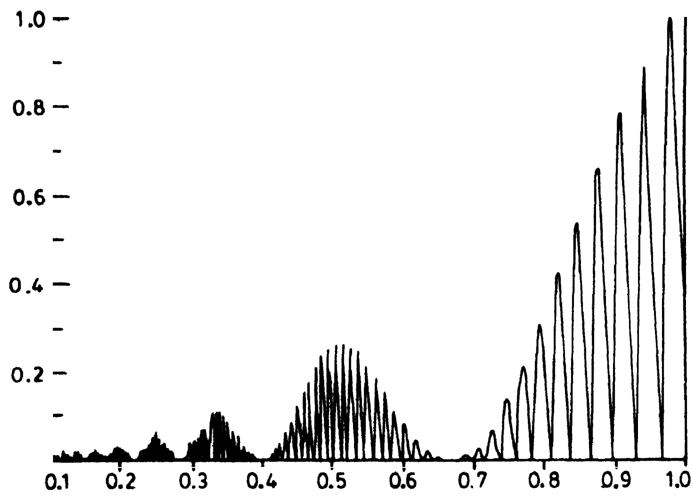


Figure 7. Intensity distribution as a function of wavelength in an echelette grating. The parameters are $N = 30$, $a = b = \Psi = 1.0$, $\gamma = -1$ and $\nu = 1$.

grating, is shown in Figure 7. The maximum peak is obtained at 0.95 cm. The position of the peak depends upon the geometrical dimension of the echelette. Choosing the proper blazed wavelength, we can optimise the intensity by judicious selection of the geometrical parameters. It has been found that 10 steps for an echelon and 10 corrugations for an echelette is usually sufficient for reasonable diffraction efficiency. The grating sizes usually vary from 20 cm to 50 cm in the mm wave range.

The antennas based upon these gratings are expected to have good intensity, efficiency and resolving power along with all the other unique properties associated with mm wave band. The proper choice of the geometrical parameter will also make the construction and fabrication cost economic.

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